Sympathetic cooling and collisional properties of a Rb-Cs mixture

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We report on measurements of the collisional properties of a mixture of ^{133}Cs and ^{87}Rb atoms in a magnetic trap at μK temperatures. By selectively evaporating the Rb atoms using a radio-frequency field, we achieved sympathetic cooling of Cs down to a few μK. The inter-species collisional cross-section was determined through rethermalization measurements, leading to an estimate of $a_s = 595\, a_0$ for the s-wave scattering length for Rb in the $|F = 2, m_F = 2\rangle$ and Cs in the $|F = 4, m_F = 4\rangle$ magnetic states. We briefly speculate on the prospects for reaching Bose-Einstein condensation of Cs inside a magnetic trap through sympathetic cooling.

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Laser cooling of neutral atoms, combined with evaporative cooling in conservative (magnetic and optical) traps, has led to a number of important breakthroughs in atomic physics, most notably the observation of Bose-Einstein condensation (BEC) in a dilute gas of alkali atoms in 1995 [1]. In recent years, research on ultra-cold atoms has expanded into the realms of atomic mixtures. Adding a second atomic species has, among other things, opened up the possibility to sympathetically cool one atomic species through collisional energy exchange with the other species [2]. On the one hand, this has proved an invaluable tool for reaching the quantum degeneracy regime with fermionic atoms for which Pauli blocking reduces the evaporative cooling efficiency at low temperatures. On the other hand, ultra-cold atomic mixtures are also interesting in their own right. In particular, the possibility of creating cold heteronuclear molecules could be an important ingredient in neutral atom quantum computing due to the expected large permanent dipole moment of such molecules. Furthermore, ultracold mixtures can lead to interesting new quantum phases when loaded into an optical lattice [3]. A large number of mixtures has been studied in magneto-optical traps (MOTs) [4, 5], and recent experiments by Kerman *et al.* [6, 7] have yielded information about the rovibrational structure of the ^{85}Rb^{133}Cs molecule. However only a few combinations of ultra-cold atoms have been experimentally investigated in conservative traps, among them Li-Cs [8], K-Rb [9, 10], and Na-Li [11].

In this work we study the collisional properties of a mixture of ultra-cold ^{87}Rb and ^{133}Cs atoms in a magnetic trap. Both Rb and Cs have been used in laser cooling of atoms for more than fifteen years now and are important as time and frequency standards. However, not much is known about their interatomic potentials and collisional properties. While for the lighter alkalis the interatomic potentials can be calculated relatively easily, it has not as yet been possible to do the same for the Rb-Cs potential. Jamieson *et al.* [12] calculated the collisional parameters using several similar-looking choices for the interatomic potentials, and found that even for small changes in the potential the s-wave scattering length varies by up to two orders of magnitude.

The experimental apparatus used for this work is similar to our Rb-BEC setup described in detail elsewhere [13]. We use a double-chamber vacuum system with a 2D collection MOT in the upper chamber and a six-beam MOT in the lower chamber. In order to trap and cool both Rb and Cs atoms, the trapping and re-pumping light for the two species is superimposed and the same optics (mirrors, lenses and waveplates) is used to create the beams for both MOTs. Once the atoms have been transferred into the lower MOT, after a brief compressed MOT and molasses phase the trapping beams are switched off and the atoms are optically pumped into the $|F = 2, m_F = 2\rangle$ and $|F = 4, m_F = 4\rangle$ magnetically trappable states of Rb and Cs, respectively. Immediately after that, the time-averaged orbiting potential (TOP) magnetic trap is switched on. Since the two atomic species have different equilibrium positions in the magnetic trap (due to gravitational sag), the positions of the MOTs have to be adjusted accordingly in order to avoid subsequent oscillations in the TOP trap. This is achieved by tuning the radiation pressure in the MOT using the (wavelength-selective) quarter-waveplates inserted into the optical path of the trapping beams.

In order to demonstrate sympathetic cooling, after loading the atoms into the magnetic trap we performed circle-of-death evaporative cooling by continuously reducing the strength of the rotating bias field. This cooling technique is not species-selective as the circle-of-death is defined by the rotating zero of field created by the (static) quadrupole and the (rotating) bias field. Hence, cooling one or the other species separately (i.e. loading only that species into the MOT) makes little difference.

We then proceeded to apply a radio-frequency field resonant with a $\Delta m_F = \pm 1$ Zeeman transition in the Rb atoms. By ramping down the frequency of the RF-field, forced evaporative cooling is induced as the radius of the surface on which atoms are transferred into untrapped states shrinks. Radio-frequency evaporation is species selective as it depends on the Zeeman-sublevel spacing. Therefore, only the Rb atoms were evaporatively cooled in this way. Nevertheless, the measured temperature of the Cs atoms exactly followed the Rb temperature down to a few μK, clearly indicating that sympathetic cooling
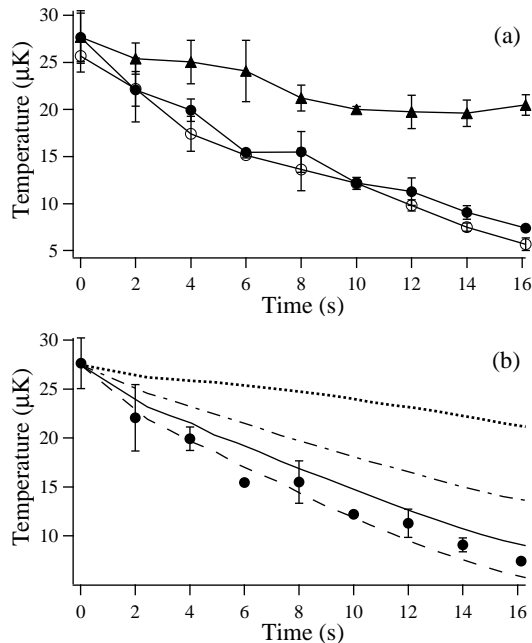
FIG. 1: (a) Sympathetic cooling of Cs atoms (filled circles) through RF-evaporation of Rb (open circles). Removing the Rb atoms before the RF-sweep, Cs atoms are only cooled slightly by residual circle-of-death evaporation at fixed bias field (triangles). (b) Comparison of experiment and Monte Carlo simulations results for Cs: no interspecies collisions (dotted line), data set C (dash-dotted line), data set A (solid line), data set B (dashed line). Rb temperatures were only slightly sensitive of the cross section.

was taking place (see Fig. 1 (a)). In fact, repeating the experiment with Cs atoms only, a much smaller cooling rate, consistent with residual circle-of-death evaporation, was observed. Initially, the atom numbers in the trap were $N_{Rb} \approx 2 \times 10^6$ and $N_{Cs} \approx 10^5$. Towards the end of the ramp, the number of Rb atoms had dropped by a factor of 10. As expected, sympathetic cooling was efficient as long as the number of Rb atoms was larger than the number of Cs atoms; once there were fewer Rb than Cs atoms, sympathetic cooling stopped.

To understand the dynamics of sympathetic cooling and extract information on the interspecies scattering properties, we performed numerical simulations using classical Monte Carlo methods [14], extended to samples of two species with different masses, atom numbers and trap frequencies. Since the known values of the C_6 coefficient for the Rb-Cs molecular potential [15] give a threshold energy for p-wave scattering of about $50\,\mu K$ [16], we took into account both the s-wave and the the p-wave contributions to the interspecies elastic cross section. Using the effective range approximation [17, 18], the s-wave term was written in terms of a scattering length a and an effective range r_e, while the p-wave term was expressed

in terms of a p-wave volume A_1 [19]:

$$\sigma_{tot} = \frac{4\pi a^2}{(1 - \frac{1}{2}ar_ek^2)^2 + a^2k^2} + \frac{12\pi A_1^2 k^4}{1 + A_1^2 k^6} \quad (1)$$

where k is the modulus of the wavevector $\mathbf{k} = \mu \mathbf{v_R}/\hbar$ of the relative motion, with μ the reduced mass of the colliding particles. The angular dependence of the $l = 1$ partial wave does not affect the efficiency of the p-wave contribution in the interspecies thermalization process (in contrast to single-species cross-dimensional relaxation, where it reduces the p-wave contribution by a factor 3/5 [20]). To analyze the experimental results, we considered the theoretical sets of scattering parameters $\{a, r_e, A_1\}$ for the triplet interaction reported in [12], corresponding to data set A = $\{595.2a_0, 190.2a_0, -168.5 \times 10^4\,a_0^3\}$, data set B = $\{177.2a_0, 126.4a_0, -4681 \times 10^4\,a_0^3\}$, data set C = $\{-317.6\,a_0, 424.2\,a_0, -112.3 \times 10^4\,a_0^3\}$ and data set D = $\{-45.37\,a_0, 3075\,a_0, -84.22 \times 10^4\,a_0^3\}$ (where a_0 is the Bohr radius). Numerical simulations using those parameters showed that only the two sets A and B were consistent with the observed efficiency of the sympathetic cooling (Fig. 1 (b)). However, systematic effects mainly related to the uncertainties in the efficiency of the evaporation processes prevented an accurate extraction of the scattering parameters from this data.

In order to obtain a more accurate measurement of the scattering cross section, we performed rethermalization measurements. First, Rb and Cs were cooled down to temperatures between $5\,\mu K$ and $60\,\mu K$ by circle-of-death evaporative cooling. Thereafter, a radio-frequency ramp was applied in such a way that the Rb atoms were cooled, but with a fast enough sweep so that there was no energy exchange between Cs and Rb during the evaporation time. At the end of the RF ramp there was thus a temperature difference between the Rb and Cs atoms [21]. The mixture was then held in the magnetic trap for up to $20\,s$ and the temperatures of both species were measured as a function of time. These measurements were repeated for various mean temperatures of the mixture.

Figure 2 shows the result of such a rethermalization measurement. In order to suppress systematic effects as much as possible, for each experimental run we measured both the Rb and Cs temperatures *without* the other species by eliminating one or the other through a resonant flash before the rethermalization process started. Typically, we observed single-species heating rates of up to $350\,nK\,s^{-1}$.

Rethermalization techniques have been extensively used to measure collisional scattering lengths and p-wave cross sections [9, 18, 22, 23, 24]. For mixtures of two clouds prepared at different temperatures, the relaxation of the temperatures due to elastic collisions with a certain constant cross section proceeds exponentially with a rate that can be calculated analytically through the model of [8]. From the rates obtained by exponential fits of observed thermalizations one can generally extract the value of the cross section. We extended that model to cross sections that explicitly depend on the energy of
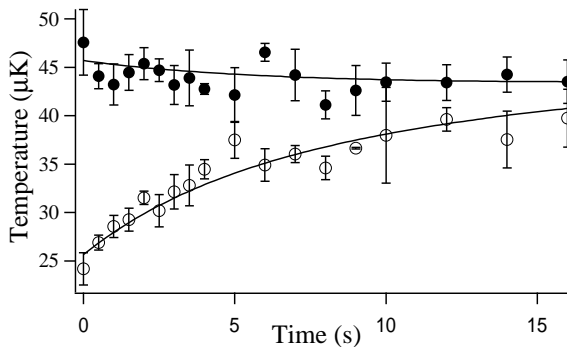
FIG. 2: Rethermalization in a Rb-Cs mixture. The initial difference between the Rb temperature (open circles) and the Cs temperature (filled circles) was created by a fast RF-evaporation of the Rb atoms. The solid lines are best fits obtained by a numerical integration of the differential equations describing the rethermalization process (see text).

the colliding particles (as in Eq. 1). In this case the relaxation rate of the temperatures in the mixture depends linearly on the effective cross section σ_e [18, 25, 26] which, in the case of eq. 1, is:

$$\sigma_e = \int_0^\infty dx\, x^5 e^{-x^2} \left(\frac{4\pi a^2}{(1 - \frac{1}{2}Car_e x^2)^2 + Ca^2 x^2} + \frac{12\pi C^2 A_1^2 x^4}{1 + C^3 A_1^2 x^6} \right) \qquad (2)$$

where $C = 2\mu k_B (m_1 T_2 + m_2 T_1)/(\hbar^2 M)$, $M = m_1 + m_2$, and k_B and $\hbar$ are the Boltzmann and the Planck constants, respectively.

We checked that exponential fits to this model and to Monte Carlo simulations gave the same thermalization rates to within a few percent [27]. However, due to the decay of the number of atoms during the thermalization and to the observed intrinsic heating independent of the interspecies interactions, we could not determine the effective cross section through a simple exponential fit to the data [28]. Those cross sections were determined by running a numerical simulation using the model discussed above for different σ_e and initial temperatures T_0^{Rb} and T_0^{Cs} of the two species, taking into account the experimental single-species heating rates and atom number decay. We then compared the results of these simulations with the experimental data, and from the combination of parameters giving the least χ^2 we finally determined σ_e. The results of this analysis are plotted in Fig. 3 as a function of temperature (initial weighted average temperature of the mixed sample).

Having measured the effective scattering cross-sections, we calculated the effective cross sections corresponding to the scattering parameters predicted by Jamieson et al. [12] for the temperature range relevant to our experiment. The agreement with our data is best for the scattering parameters of data set A, i.e.

for the combination $a = 595.2\,a_0$, $r_e = 190.2\,a_0$ and $A_1 = -168.5 \times 10^4\,a_0^3$ (see Fig. 3).

We note here that due to imperfect optical pumping (and, possibly, other depolarizing processes during the evaporation cycle), both the Rb and Cs clouds had admixtures of atoms in other Zeeman sublevels. In the case of Rb, around 90 percent of the atoms were in the desired state $|F = 2, m_F = 2\rangle$, with around 10 percent in the $|F = 2, m_F = 1\rangle$ sublevel, while for Cs we measured (by performing a Stern-Gerlach type experiment to separate the Zeeman levels in time-of-flight) relative populations of 70-80 percent in the $|F = 4, m_F = 4\rangle$ sublevel and 20-30 percent in $|F = 4, m_F = 3\rangle$. This posed two problems in interpreting our data. Firstly, the scattering cross-sections for atoms in the various Zeeman sublevels are not necessarily the same. Since we could not eliminate the populations in the other sublevels, we can only quote them here to indicate the possible error involved in our determination of the Rb$|F = 2, m_F = 2\rangle$ − Cs$|F = 4, m_F = 4\rangle$ cross-section. Secondly, the presence of other Zeeman sublevels distorted the density profiles from which we calculated the Rb and Cs temperatures by fitting gaussian curves to the clouds. This problem was solved by fitting a double-gaussian curve with a fixed separation (calculated from the known trap parameters and magnetic moments of the atoms) and extracting the temperature from the widths of these two gaussians.
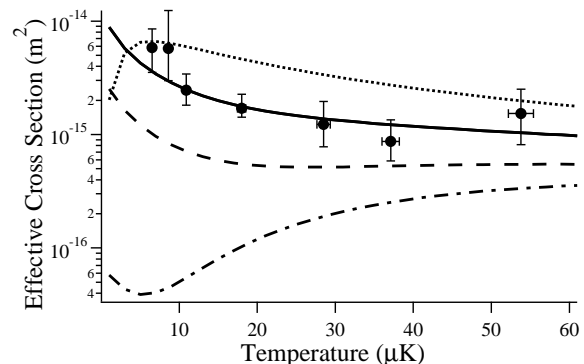

FIG. 3: Effective elastic scattering cross sections for Rb-Cs collisions as a function of temperature. The theoretical predictions by Jamieson et al. [12] plotted in this graph are: data set B (dotted line), data set A (solid line), data set C (dashed line) and data set D (dash-dotted line).

Concerning the inelastic collisional properties of the Rb-Cs mixture, we found that in the temperature range $5 - 40\,\mu K$ and for typical densities of $0.5 - 2 \times 10^{10}\,cm^{-3}$, no additional losses in either Rb or Cs in the presence of the other species occurred. We can, therefore, put the upper limit of $\sim 10^{-12} cm^3 s^{-1}$ on the inelastic coefficient for Rb-Cs collisions in magnetic fields in the range $4 - 40\,G$. In the same range we also performed a slow sweep of the bias field, but observed no pronounced losses. This rules

out the possibility of broad inter-species Feshbach resonances (as observed recently for $Na - Li$ mixture [11]). In future experiments it will be interesting to extend the search for such resonances to higher fields and to other hyperfine states of Rb and Cs, as they could make possible the creation of ultra-cold heteronuclear RbCs-molecules directly in the magnetic trap.

Finally, the fact that Cs can be sympathetically cooled by Rb and that the scattering length for inter-species collisions is large leads us to speculate whether it might be possible to reach Bose-Einstein condensation of Cs inside a magnetic trap using a sympathetic cooling approach. Although Cs was recently condensed inside an optical trap [29], it would still be interesting to achieve condensation in a magnetic trap, thus avoiding the complicated setup of [29]. Since in our current experiment the number of Rb atoms we could initially trap was too small to extend the sympathetic cooling below a few μK, we conducted Monte-Carlo simulations with larger numbers of atoms. Our simulations took into account the inelastic losses especially of Cs, which in the $|F = 4, m_F = 4\rangle$ Zeeman sublevel has a zero-energy resonance [30] associated with a large inelastic collision rate responsible for the failure of all attempts so far to reach Bose-Einstein condensation in a magnetic trap (for similar reasons, it has not been possible to condense the $|F = 3, m_F = -3\rangle$ level, either). Running simulations with up to 2×10^7 Rb atoms in the $|F = 2, m_F = 2\rangle$ sublevel, 10^5 Cs atoms in $|F = 4, m_F = 4\rangle$ and an initial temperature of $10\,\mu$K

for both species clearly showed that even with a large (but still realistic) number of Rb atoms and very low final trap frequencies (chosen so as to reduce the Cs density and hence inelastic losses), it is not possible to reach quantum degeneracy in such a scheme. However, using the $|F = 1, m_F = -1\rangle$ and $|F = 3, m_F = -3\rangle$ sublevels for Rb and Cs, respectively, we found that with the same numbers of atoms as in the first simulation and the same initial temperature, the threshold for condensation of Cs was reached with roughly 5×10^4 Cs atoms left in the mixture[31].

In conclusion, we have demonstrated sympathetic cooling of Cs atoms in a Rb-Cs mixture and characterized ultra-cold collisions between the two species by measuring rethermalization rates. Our results are consistent with a large interspecies s-wave scattering length around $595\,a_0$. Starting with two orders of magnitude more Rb atoms (around 2×10^7) than available in the present experiment, and by trapping Rb and Cs in the lowest respective hyperfine states, it seems feasible to reach Bose-Einstein condensation of Cs in a magnetic trap.

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